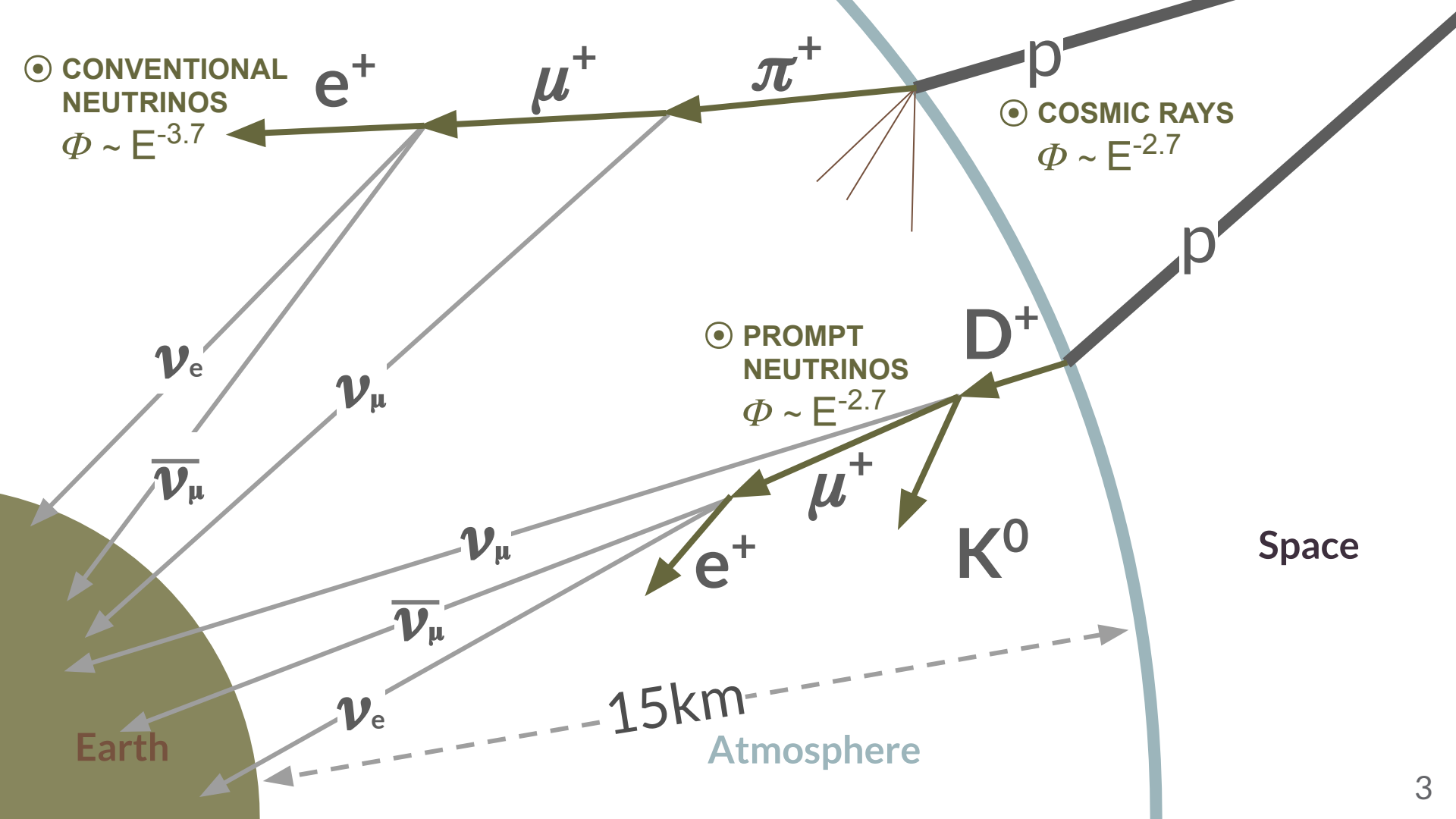# Atmospheric neutrinos in the far detector

Austin Schneider
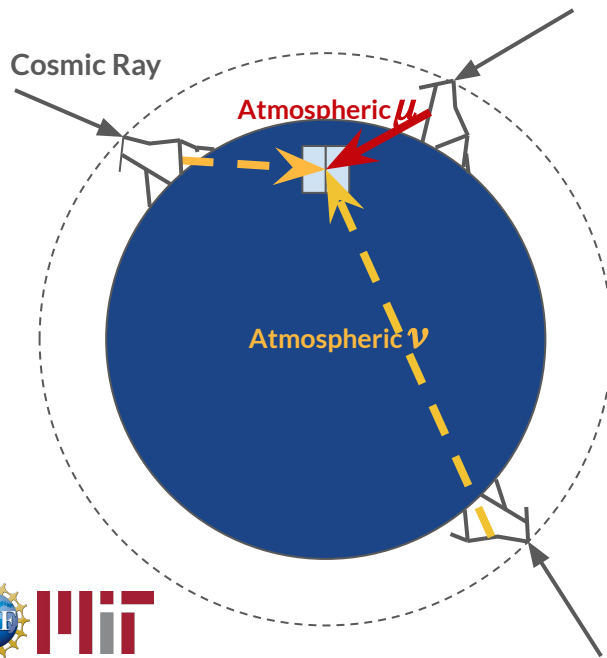
Outline

- Atmospheric neutrinos

- Above 100 GeV

  - Planned sterile search

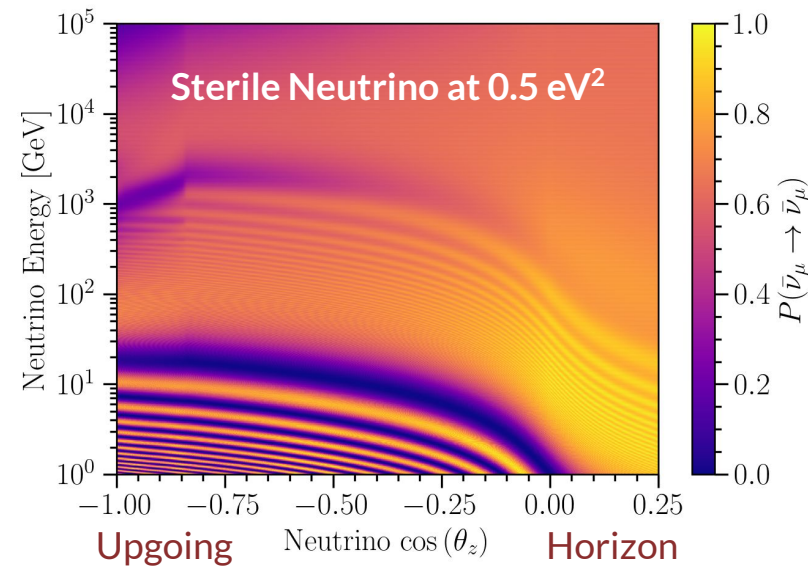- Below 100 GeV

  - Analysis framework

⊙ CONVENTIONAL NEUTRINOS
$\Phi \sim E^{-3.7}$

e^+ μ^+ π^+ p

⊙ COSMIC RAYS
$\Phi \sim E^{-2.7}$

p

ν_e

ν_μ

$\overline{\nu}_\mu$

⊙ PROMPT NEUTRINOS
$\Phi \sim E^{-2.7}$

D^+

ν_μ

$\overline{\nu}_\mu$

μ^+

e^+

K^0

Space

ν_e

15km

Earth

Atmosphere

3

Atmospheric neutrinos

- Neutrinos from cosmic ray interactions

- Wide range of energies and baselines

- From GeV to PeV and km to 1.2e4 km

- Mostly Mu flavor, ½ to 1/10 electron flavor depending on energy

- Spectrum peaks just below 1 GeV

- Drops off as $E^{-3.7}$

- Oscillation fits now happen in 2D

Atmospheric neutrinos (in) DUNE

- Rapidly falling flux → low stats at high energies

- Below 100 GeV
  - Interactions in the detector volume are sufficient
  - PID is possible inside the detector
  - Access to tau appearance

- Above 100 GeV
  - < 30 interactions in a module per year across all flavors
  - Incoming muons → > 200 events per module per year
  - Access to muon disappearance

- Steriles
- Lorentz violation
- NSIs
- Unitarity

- Neutral heavy leptons
- Mass varying neutrinos
- Decoherence

ν_τ

μ

ν

μ
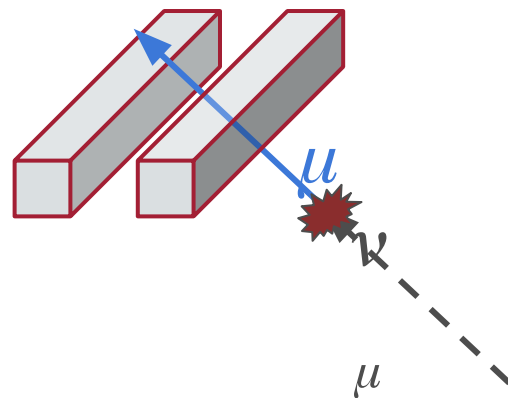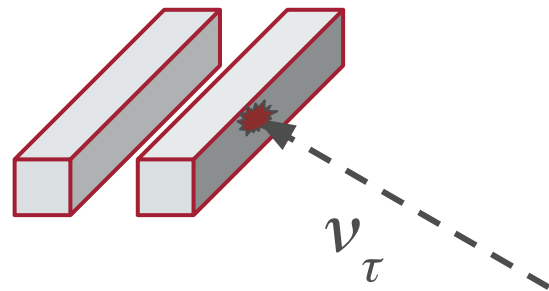
Above ~50 GeV
Incoming muons

3+1 / through-going muons introduction
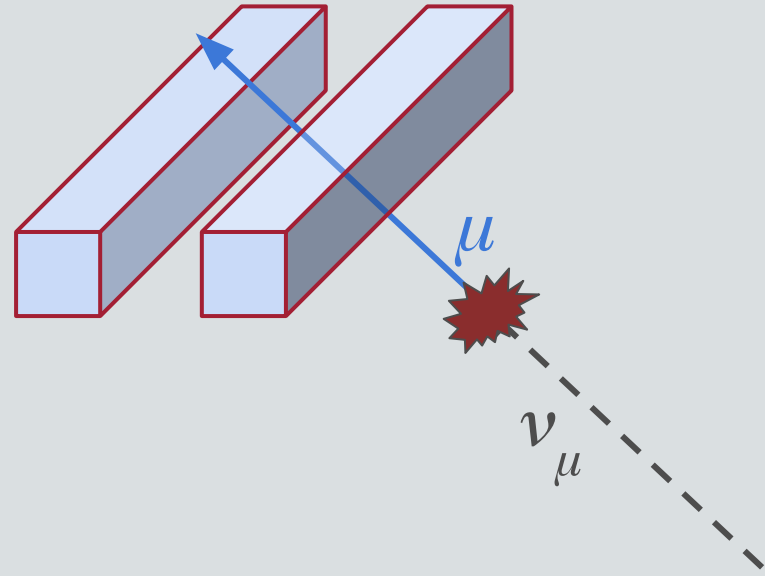
- Coming from IceCube

- DUNE far detector is sensitive in a window: 50 GeV to 1 TeV
  - Interesting for 3+1, Lorentz violation, NSI, etc.

- Using open source IceCube atmospheric tools adapted for DUNE
  - Oscillations [nuSQuIDS]
  - Muon propagation [PROPOSAL]
  - Neutrino injection and weighting [LeptonInjector, LeptonWeighter]

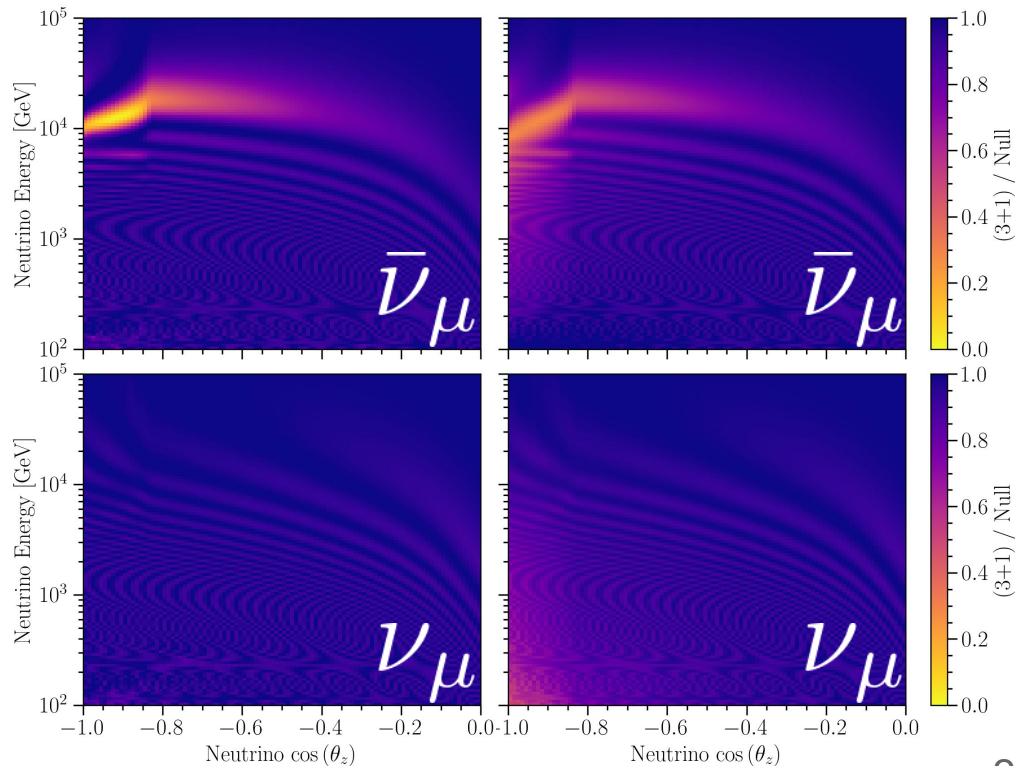# Effect of θ_{34} in 3+1 scenario
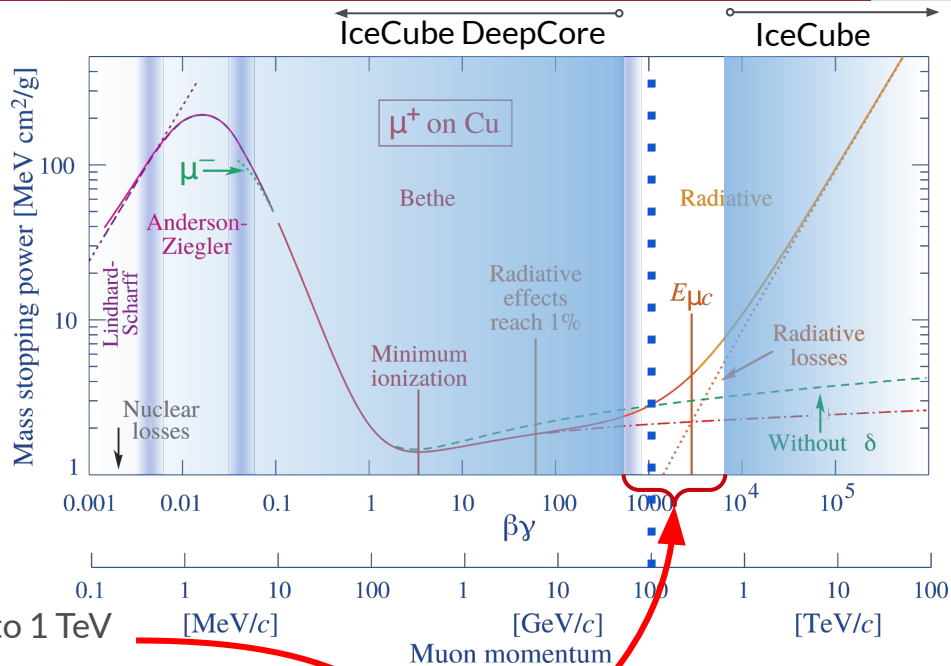
$\theta_{34}=0$, $\Delta m^2=4.5 eV^2$ $\theta_{34}=0.3$, $\Delta m^2=4.5 eV^2$
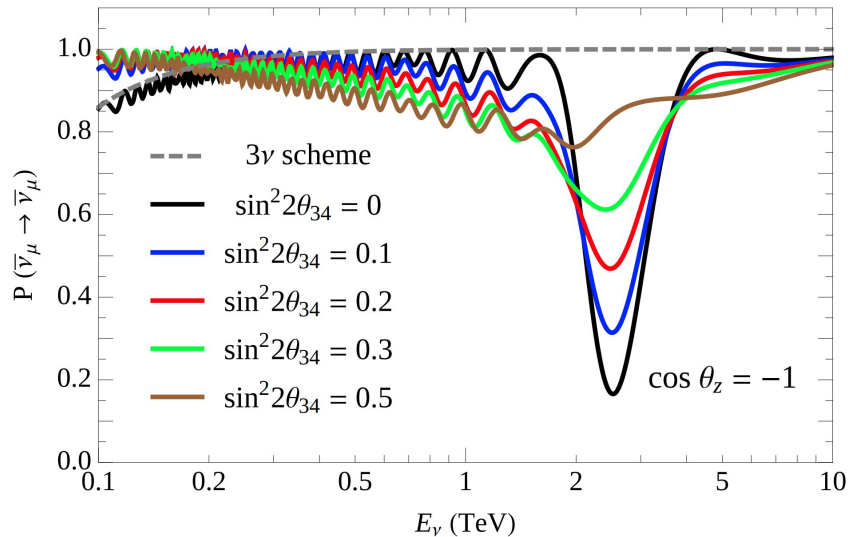
Esmaili, A., Smirnov, A.Y., *J. High Energ. Phys.* 2013, 14 (2013).
https://doi.org/10.1007/JHEP12(2013)014

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3+1 signature in DUNE

- Neutrino and muon physics fully simulated

- Very simplified detector response (missing detector sim)

- ~7 starting muons per year per module above 100 GeV

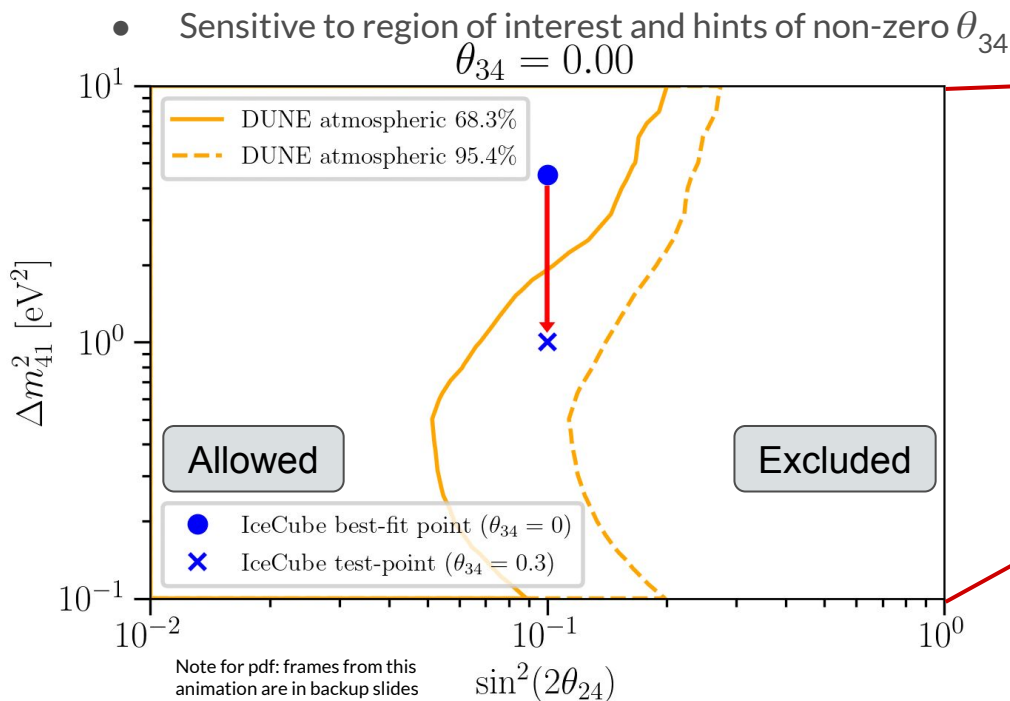- ~230 upgoing through-going muons per year per module above 100 GeV
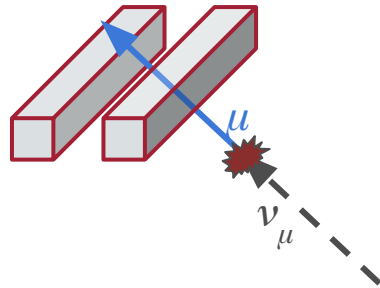
- (3+1) neutrino expectation vs 3 neutrino expectation

- Particularly sensitivity to non-zero θ_{34}
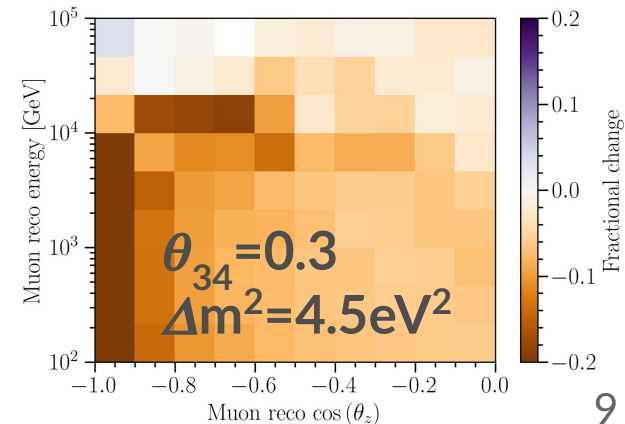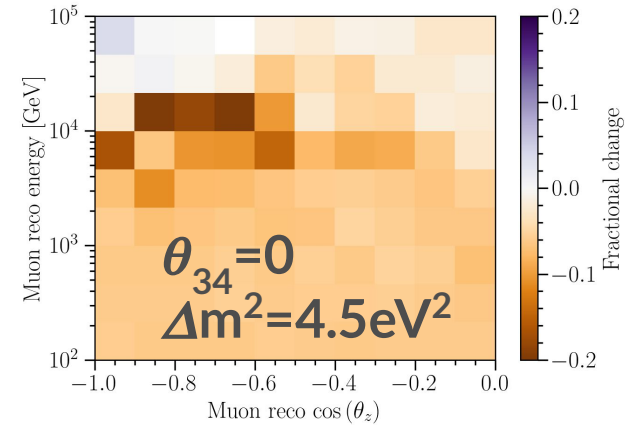
Sensitivity to 3+1 scenario

- 9 module-years (first ~5 years of operation)
- 5% normalization uncertainty, 0.01 CR spectral uncertainty
- 3 neutrino oscillation parameters fixed
- Wilks' w/ 3 degrees of freedom (using Asimov data)
- Sensitive to region of interest and hints of non-zero θ_{34}

$\theta_{34} = 0.00$

IceCube results θ_{34}=0
8 years of data
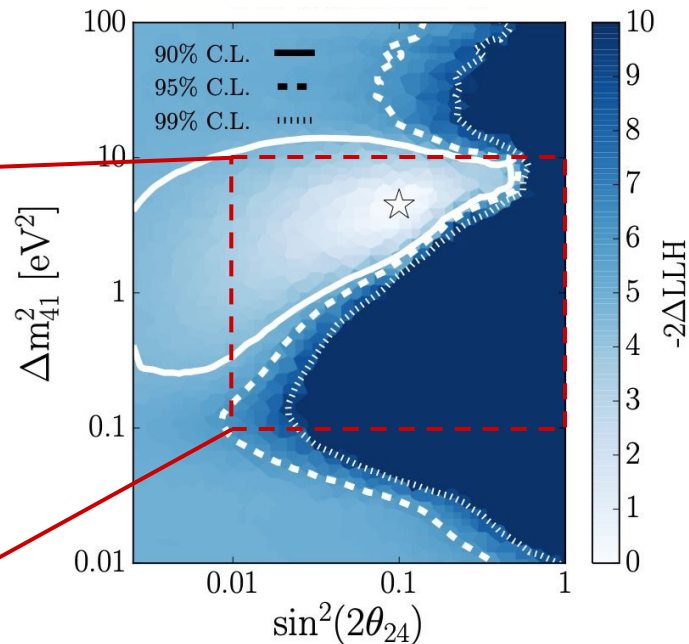
IceCube Collaboration, Phys. Rev. D 102, 052009
https://doi.org/10.1103/PhysRevD.102.052009

Note for pdf: frames from this animation are in backup slides

Many sectors to explore

- Steriles with non-zero θ_{34}

- Lorentz violation

- Non standard interactions

- Neutral heavy leptons

- Dark matter searches

- Neutrino decay

Below ~200 GeV
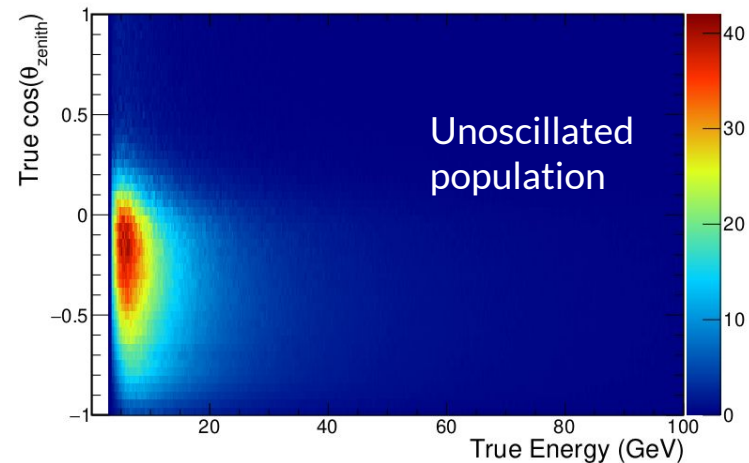# Contained vertex

ν_τ
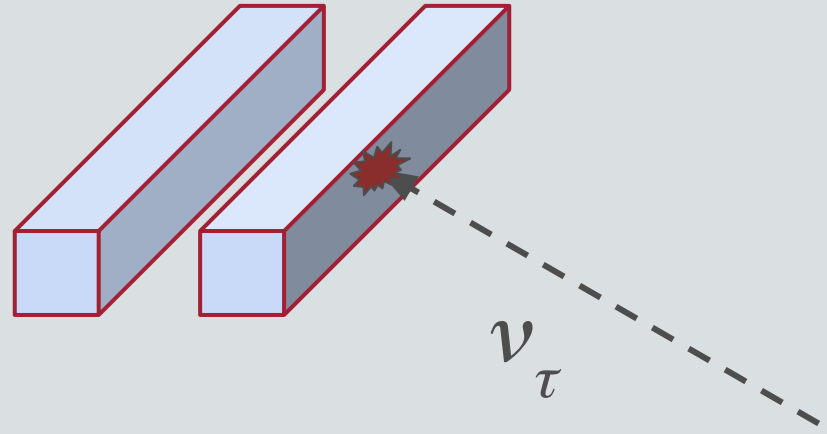
Below ~200 GeV

- CAFAna framework used for LBL analysis: **Chris Backhouse (UCL)** is adapting it for atmospheric neutrinos

- Using the same tooling means we can make use of LBL reconstruction, systematic errors etc. with minimal effort

- Selection, reconstruction, and analysis methods will be similar

- Recently added Earth oscillations

- Various BSM oscillation scenarios implemented

  - Sensitivity needs exploration

$P(\nu_\mu \rightarrow \nu_\tau)$
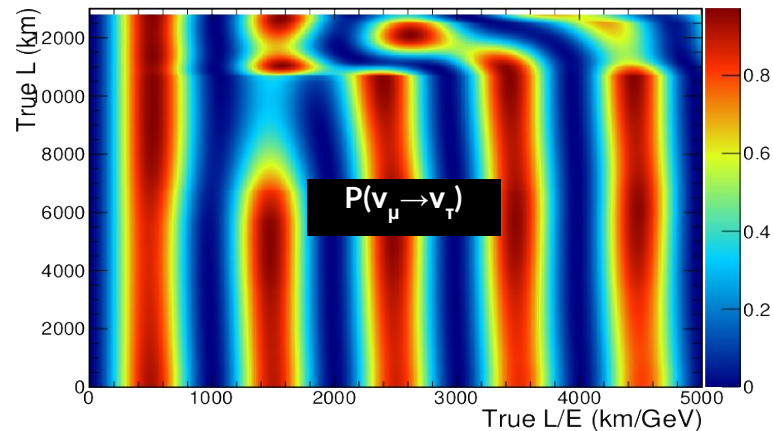
- **Proof of concept: reproducing previous $\nu_\mu \rightarrow \nu_\tau$ sensitivity from Adam Aurisano**

  - Very simple efficiency and systematic model

- Other analyses can be implemented in this same framework

- **Strong point is ν_τ detection**

Oscillation calculation

- Implementation of earth matter density profile [1][2]
- Compute 2D oscillogram using slab approximation
- Currently using CAFAna-native OscLib [3], will also interface to João Coelho's OscProb [4]

- Empirically, details of earth model don't matter much for this tau appearance analysis

- What about rapid oscillations?

$P(\nu_\mu \rightarrow \nu_\tau)$

Downgoing

Upgoing

Unoscillated population

[1] Dziewonski and Anderson, Physics of the Earth and Planetary Interiors, 25 (1981)
[2] F.D. Stacey, Physics of the Earth (Wiley, New York, 1969)
[3] https://github.com/CAFAnaFramework/OscLib
[4] https://github.com/joaoabcoelho/OscProb/
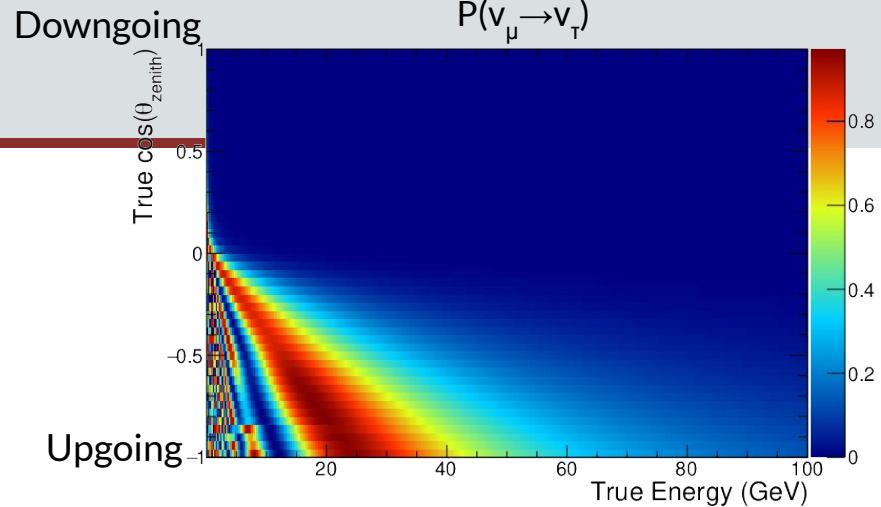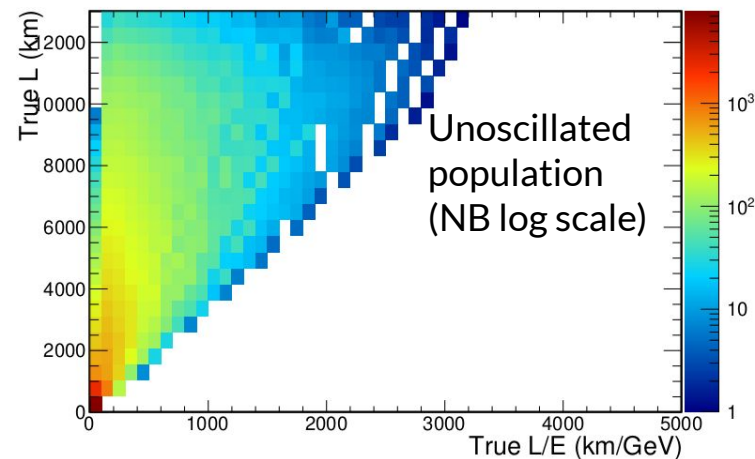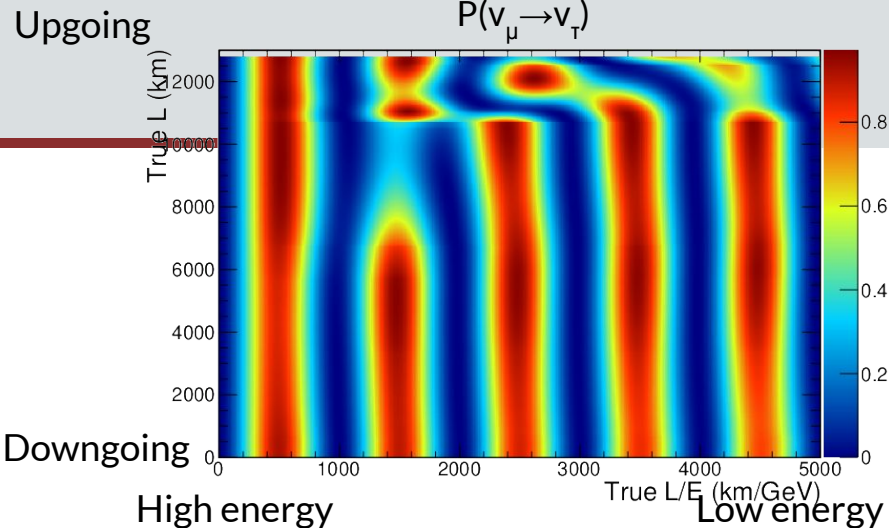
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Oscillation calculation

- Implementation of earth matter density profile [1][2]
- Compute 2D oscillogram using slab approximation
- Currently using CAFAna-native OscLib [3], will also interface to João Coelho's OscProb [4]

- Empirically, details of earth model don't matter much for this tau appearance analysis

- What about rapid oscillations?
- Alternate binning demonstrates we don't really reach the rapid regime
- Will do the analysis in this space in future

$P(\nu_\mu \to \nu_\tau)$

Upgoing

Downgoing

High energy — Low energy

Unoscillated population (NB log scale)

[1] Dziewonski and Anderson, Physics of the Earth and Planetary Interiors, 25 (1981)
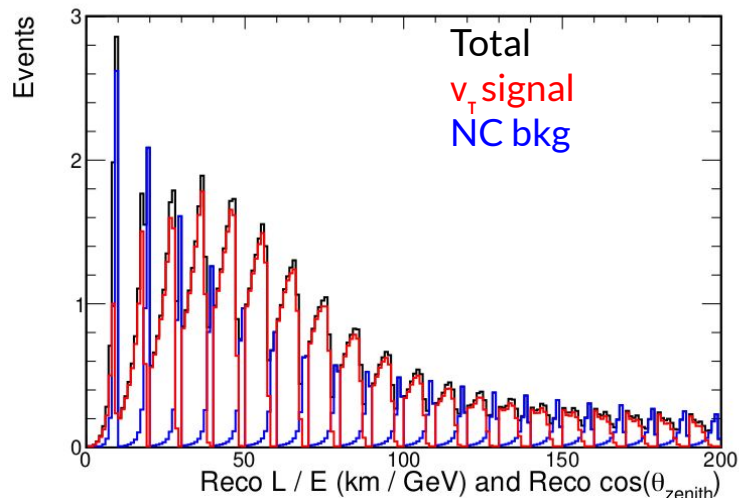[2] F.D. Stacey, Physics of the Earth (Wiley, New York, 1969)
[3] https://github.com/CAFAnaFramework/OscLib
[4] https://github.com/joaoabcoelho/OscProb/

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Oscillated spectra and sensitivities

- Analyze in 2D reco cosθ vs reco L/E space

- Oscillation probabilities allow weighting reco vs true distribution to any osc parameters

- Generate confidence intervals in a few seconds

- Fairly good agreement between **Chris's result** and **prior art**
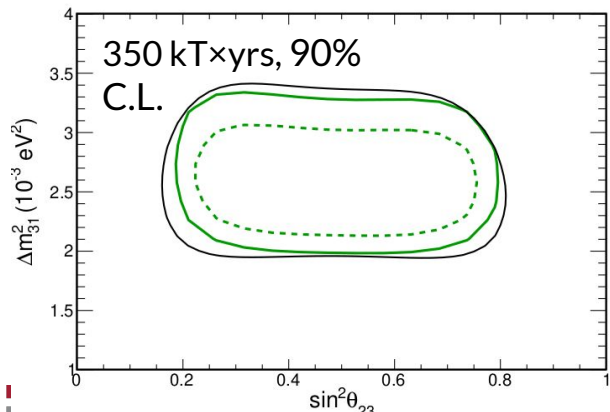
- Physics we can explore in this regime

  - Unitarity bounds
  - NSIs
  - Neutral heavy leptons
  - Dark matter (neutrino decay channel)
  - Steriles near atmospheric splitting
  - Mass hierarchy
  - CP violation
  - Others?

350 kT×yrs, 90% C.L.

$\sin^2\theta_{23}$, Δm^2_{31} (10^{-3} eV^2)

Events

Total
ν_τ signal
NC bkg

Reco L / E (km / GeV) and Reco cos(θ_{zenith})

Summary

- There is a wide energy range to work with

- Good sensitivity to scenarios explored
    - Many scenarios to explore in both energy regimes (help needed!)

- Leverage the detail provided by a LArTPC

- Events from the **bedrock ⇒ muon** disappearance measurable **above 50 GeV**

- Events in the **detector ⇒ tau** appearance / **muon** disappearance measureable in the **< 200 GeV** regime

- Tools for atmospherics are being adapted from both ends

- MIT/Harvard hosting a workshop for investigating DUNE/IceCube(upgrade) synergies [June 16th-18th]

    - Attendance will be virtual

Bonus Slides

Below ~200 GeV

- CAFAna framework used for LBL analysis: **Chris Backhouse** is adapting it for atmospheric neutrinos
  - Using the same tooling means we can make use of LBL reconstruction, systematic errors etc. with minimal effort

- **Start by reproducing previous $v_\mu \rightarrow v_\tau$ sensitivity from Adam Aurisano**
  - Very simple efficiency and systematic model

- Other analyses can be implemented in this same framework

- Using true (E,cosθ) flux*xsec and 4D (E,cosθ)true→(E,cosθ)reco smearing matrix from Adam
  - In future, load from standard CAF format - gives user control over selection/binning etc

- Flat efficiencies – 37% for v_τ, 0.5% for NC

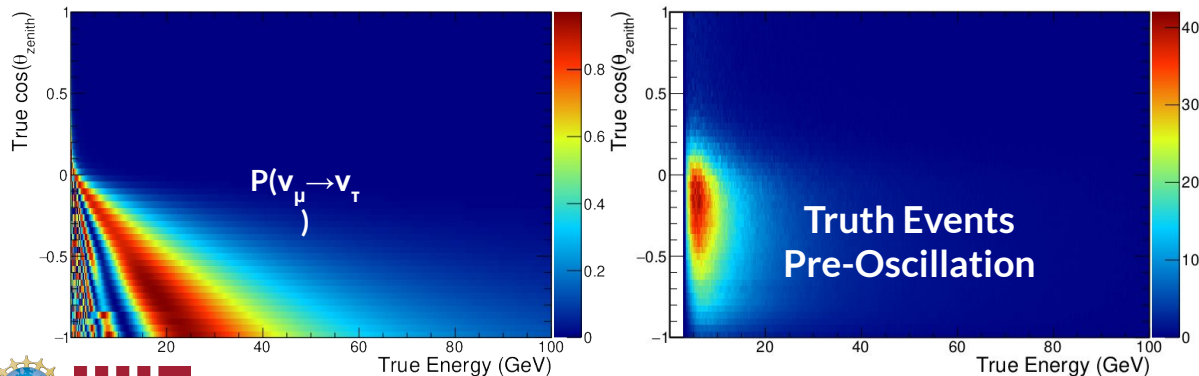- Profile over 25% overall scale systematic uncertainty

Oscillation calculation

[1] https://github.com/CAFAnaFramework/OscLib
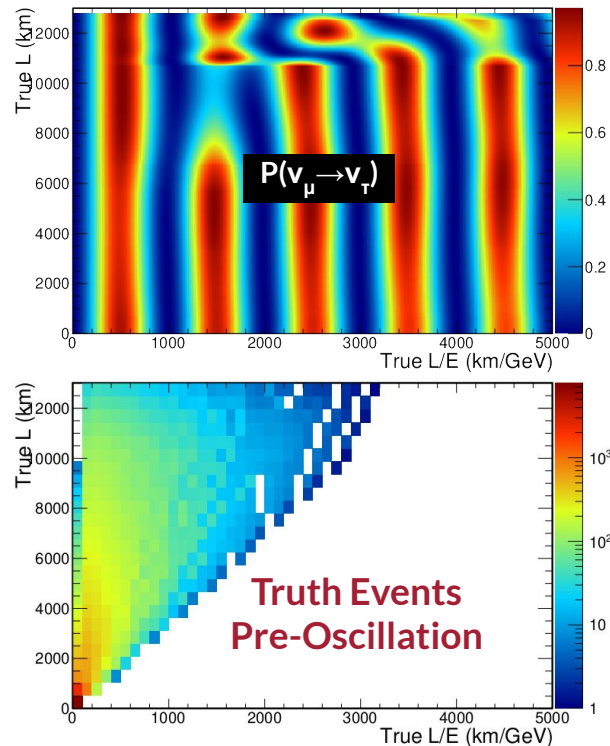[2] https://github.com/joaoabcoelho/OscProb/

- Earth oscillation calculation implemented in CAFAna-native OscLib [1], will also interface to João Coelho's OscProb [2]

- L/E space more convenient binning for oscillation calculation
  - Avoids rapid oscillations

- Not yet concerned about rapid oscillations
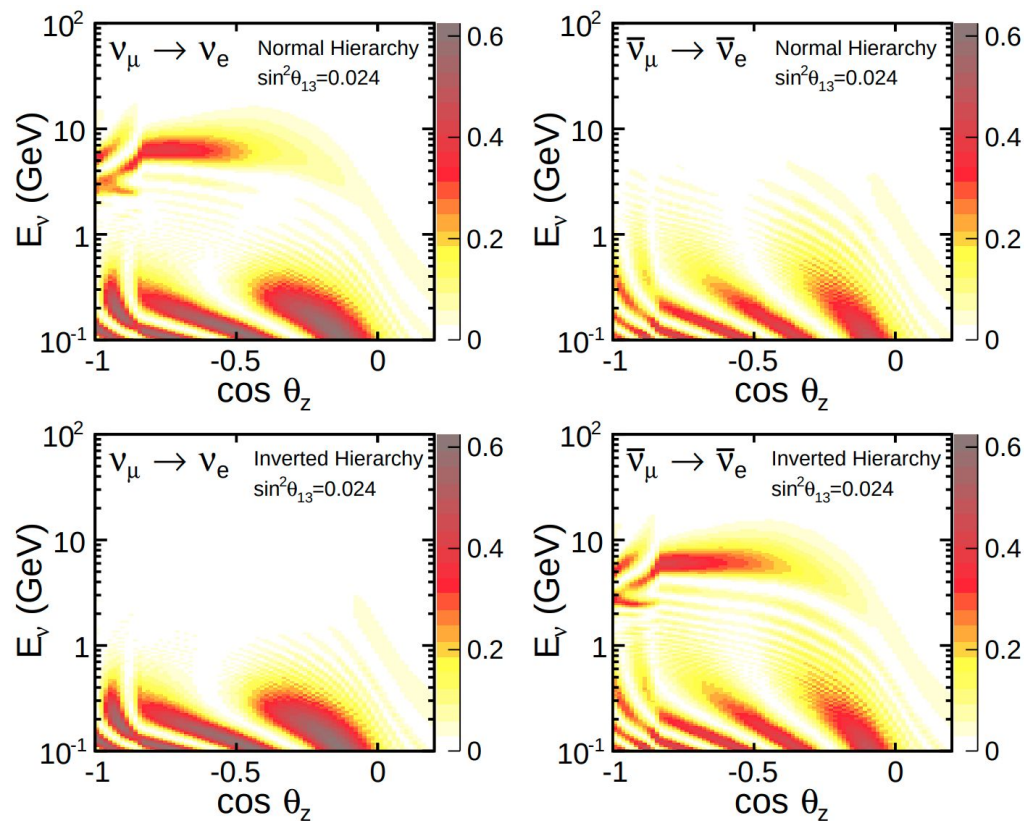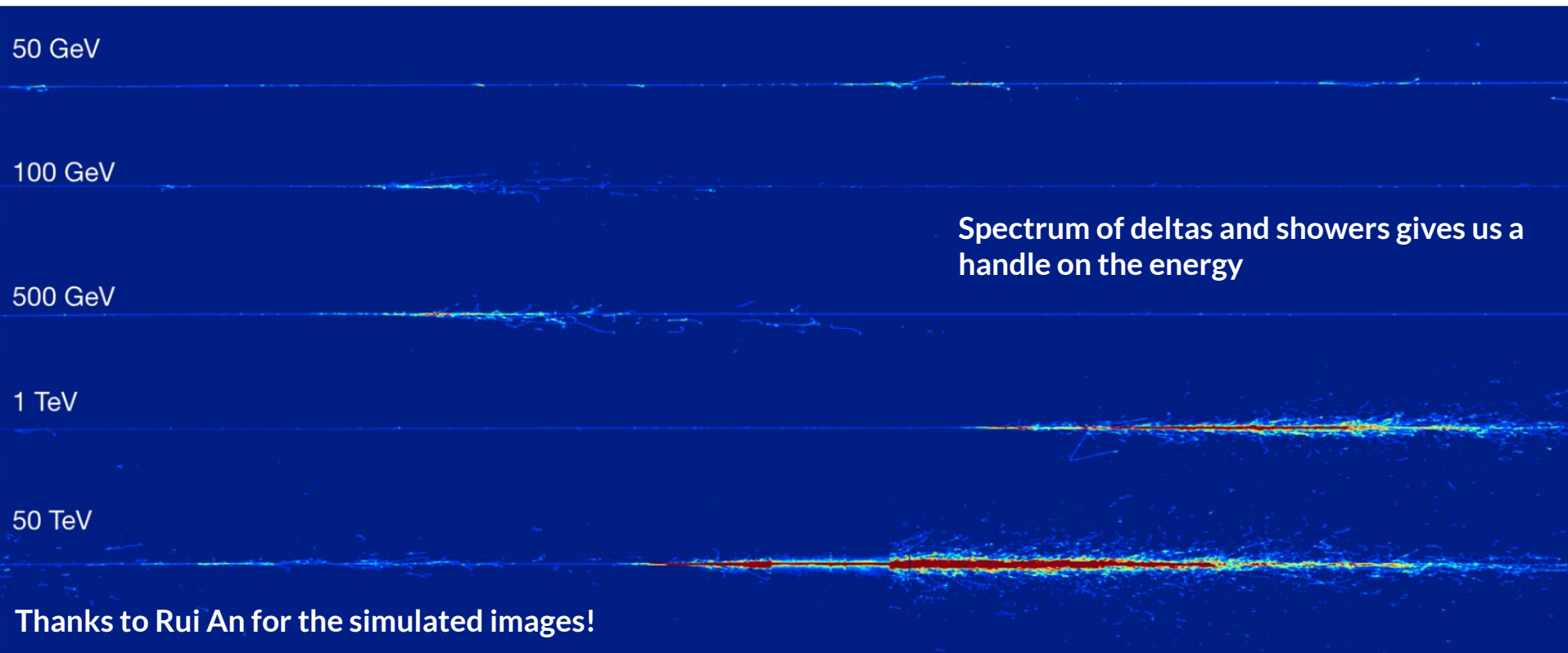 - Analysis is clear of this regime

L and L/E binning

$P(\nu_\mu \rightarrow \nu_\tau)$

cos(theta) and E binning

$P(\nu_\mu \rightarrow \nu_\tau)$

**Truth Events
Pre-Oscillation**

**Truth Events
Pre-Oscillation**

Mass hierarchy

Muons in DUNE (10 m)

50 GeV

100 GeV

Spectrum of deltas and showers gives us a handle on the energy

500 GeV

1 TeV

50 TeV

Thanks to Rui An for the simulated images!
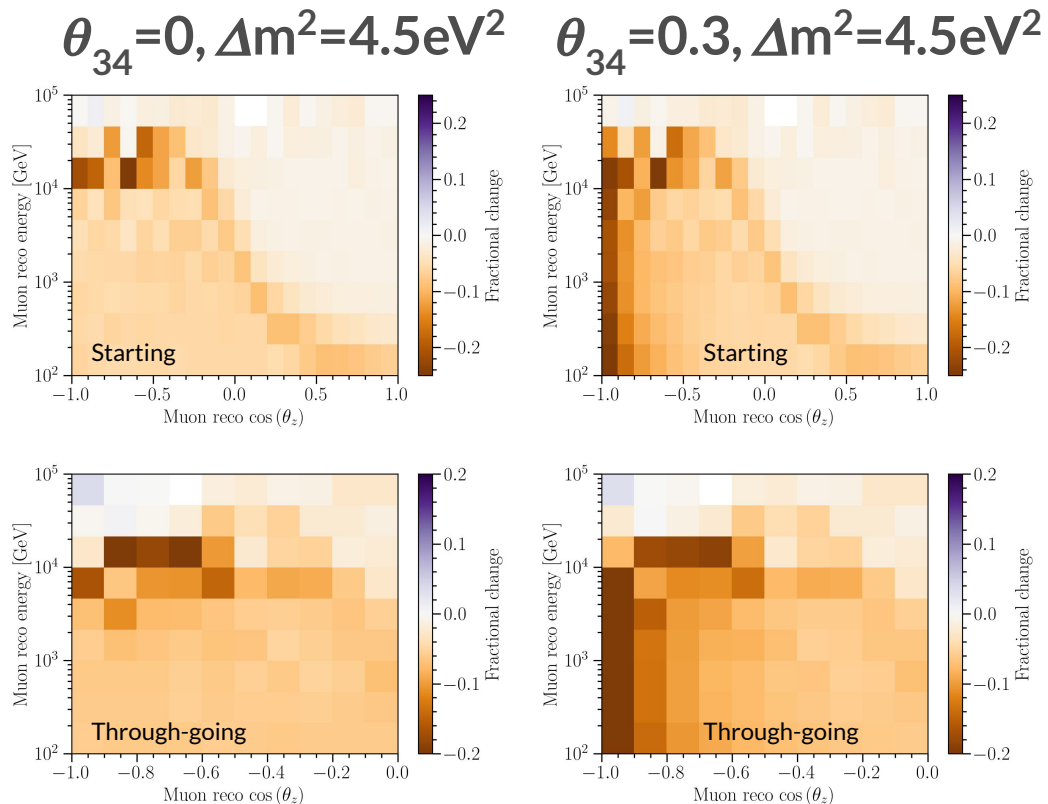
3+1 signature in DUNE

- ~14 starting muons per year per module above 100 GeV

- ~230 upgoing through-going muons per year per module above 100 GeV

- (3+1) neutrino expectation vs 3 neutrino expectation

- Particularly sensitivity to non-zero θ_{34}

$\theta_{34}=0, \Delta m^2=4.5eV^2$ $\theta_{34}=0.3, \Delta m^2=4.5eV^2$

Analysis details/assumptions

1. 3 neutrino oscillation parameters fixed
2. Directional reconstruction error negligible
3. Energy resolution of muons is 10% and 20% for starting and through-going events respectively (log-normal distributed)
4. Simple model for rock
5. 14m x 58.2m x 12m liquid argon
6. 13.9m x 58.1m x 11.9m fiducial volume
7. H3a_SIBYLL23C conventional atmospheric flux (from nuflux [https://github.com/icecube/nuflux])
8. Only numu / numubar CC DIS final states assuming CSMS cross sections
9. Total interaction cross section from CSMS (CC + NC DIS)
10. Oscillation probability computed with tau regeneration and Glashow resonance
11. Oscillation probability computed on 1 GeV to 1 PeV 101 point log energy grid * 100 point cos zenith grid
12. Detector center at -1480m from surface (perhaps this should be the top or bottom of the detector?)
13. ~250,000 simulation events at final level
14. MC statistical errors accounted for via likelihood technique [https://austinschneider.github.io/MCLLH/]
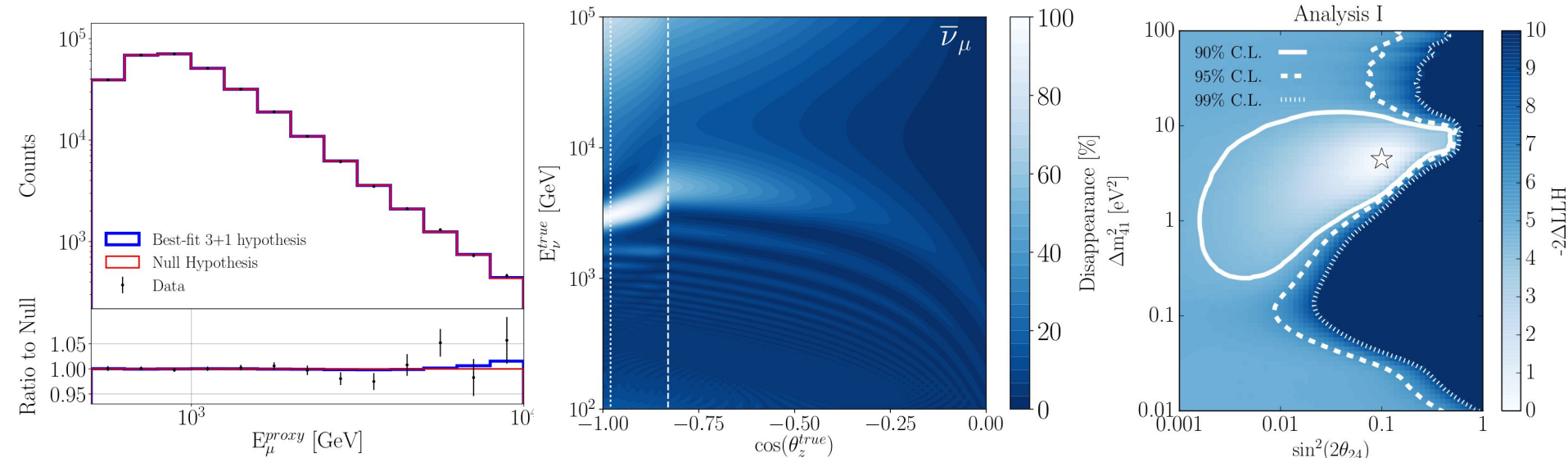
Sterile neutrinos in IceCube

- Matter effects produce resonance in numubar disappearance

- Produces a sharp feature in energy and zenith angle!

- $\Delta m^2_{41} = 1 \text{ eV}^2$, $\sin^2(2\theta_{24}) = 0.1$:
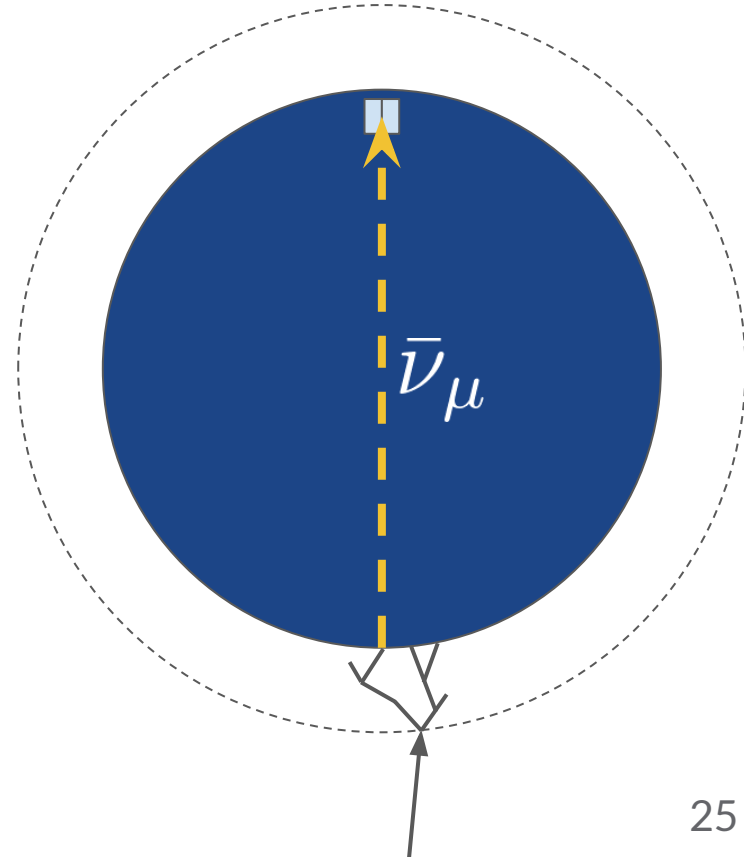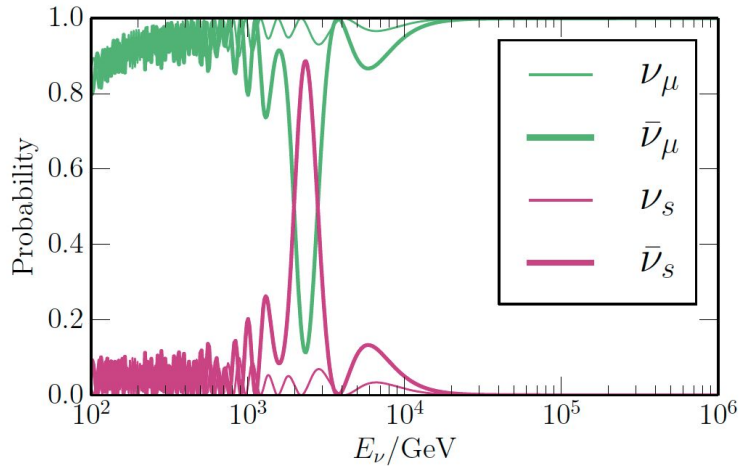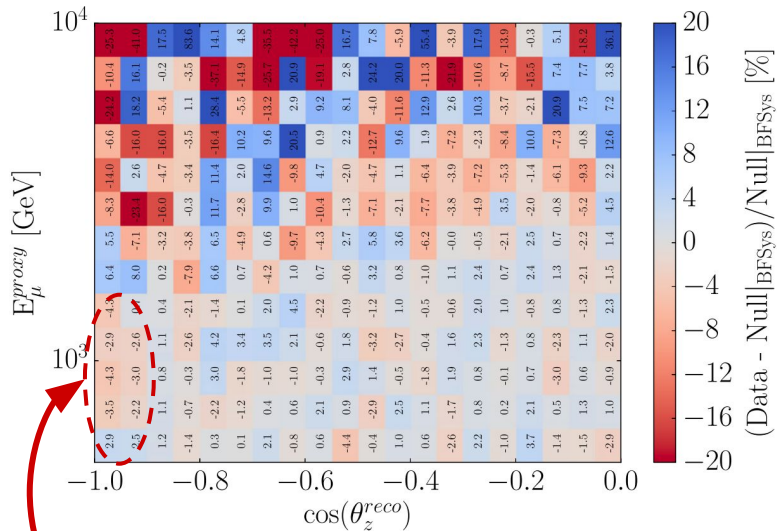
Searching for sterile neutrinos in IceCube

- Search for 3+1 matter resonance
- Scan in $\sin^2(2\theta_{24})$ and Δm^2
- θ_{34} is fixed to zero

$$E_{\text{crit}}^M = \frac{\Delta m^2 \cos(2\theta)}{\sqrt{2}G_F n_e} \approx \frac{\Delta m^2 \cos(2\theta)}{0.038(\rho[g/cm^3])}$$
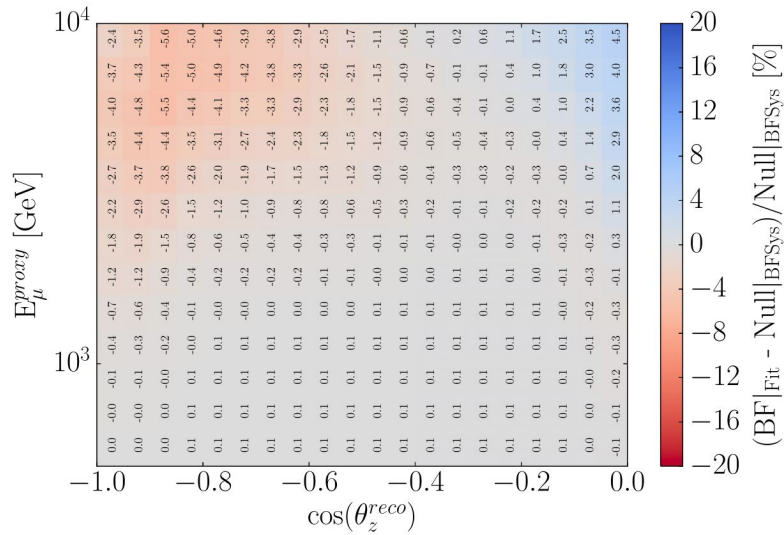
26

Data shape w.r.t. null shape

Best-Fit signal shape

Deficit persistent across many years of data

IceCube Collaboration, Phys. Rev. Lett. 125, 141801
https://doi.org/10.1103/PhysRevLett.125.141801

- Add higher dimensional operators to effective Hamiltonian

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots$$

- Causes neutrino disappearance

- Focus on mu/tau mixing ⇒ muon neutrino and muon antineutrino disappearance

- Parameterization:

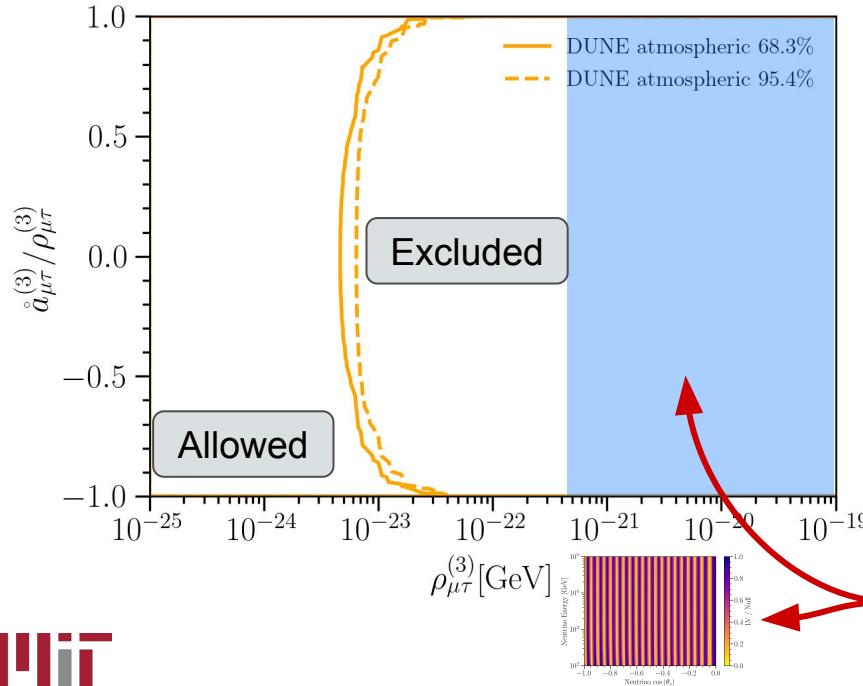 ○ Strength of LV $\quad \rho^{(3)} = \sqrt{(\mathring{a}_{\mu\mu}^{(3)})^2 + (\mathrm{Re}[\mathring{a}_{\mu\tau}^{(3)}])^2 + (\mathrm{Im}[\mathring{a}_{\mu\tau}^{(3)}])^2}$

  ○ Fraction on the diagonal $\quad \mathring{a}_{\mu\mu}^{(3)} / \rho^{(3)}$

$$\mathring{a}^{(3)} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & a_{\mu\mu} & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & a_{\tau\tau} \end{pmatrix} \qquad a_{\tau\tau} = -a_{ee} - a_{\mu\mu}$$

Lorentz Violation dimension 3 sensitivity

- 9 module-years (first ~5 years of operation)
- 5% normalization uncertainty, 0.01 CR spectral uncertainty
- 3 neutrino oscillation parameters fixed
- Wilks' w/ 2 degrees of freedom

The IceCube Collaboration. *Nature Phys* 14, 961−966 (2018).
https://doi.org/10.1038/s41567-018-0172-2

IceCube results
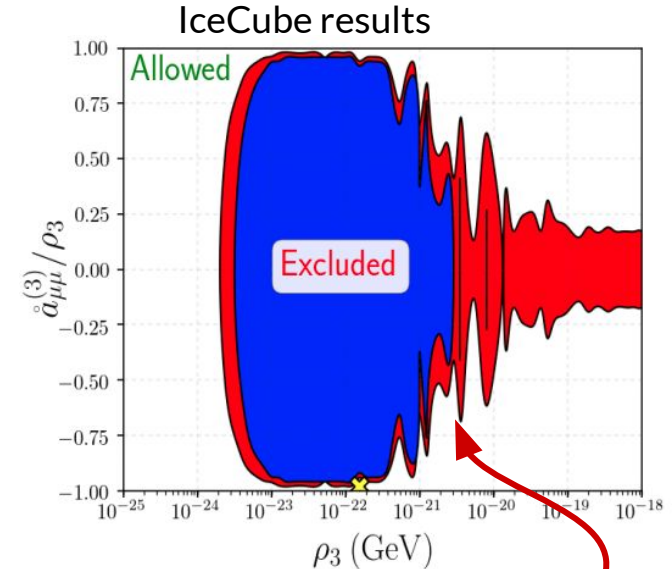
Fast oscillations, expensive to compute.
Need approximation in this regime.